October 2001 • NREL/CP-520-31144

Conference Paper

$Cu(In,Ga)Se_2$ Thin-Film Concentrator Solar Cells

Preprint

J. Ward, K. Ramanathan, F. Hasoon, T. Coutts,
J. Keane, T. Moriarty, and R. Noufi

To be presented at the NCPV Program Review Meeting
Lakewood, Colorado
14-17 October 2001

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

$Cu(In,Ga)Se_2$ Thin-Film Concentrator Solar Cells

J. Ward, K. Ramanathan, F. Hasoon, T. Coutts, J. Keane, T. Moriarty, and R. Noufi
National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401

ABSTRACT

$Cu(In,Ga)Se_2$ (CIGS) solar cells have been designed for operation under concentrated sunlight. The absorber layers were deposited *via* the three-stage evaporation process that has been responsible for record one-sun device performance. The device structure was modified for operation under concentration by reducing the thickness of the CdS window layer, enhancing the short-circuit current (J_{sc}) at the expense of open circuit voltage (V_{oc}). At 14 suns concentration, the open circuit voltage of the best device was 736 mV. The fill factor was 80.5% and the efficiency was 21.5%. This is the first report of a polycrystalline thin-film solar cell with a verified efficiency in excess of 20%.

1. Introduction

In recent years, CIGS solar cells have reached impressive levels of performance. Efficiencies of laboratory cells routinely exceed 18% [1,2,3]. Although the motivation for CIGS research has been focused on low-cost, flat-plate applications, these performance levels make CIGS an attractive option for low-to moderate-flux concentrator systems. III-V multi-junction devices have recently demonstrated efficiencies in excess of 32% [4] but their expense requires that they be used with optical systems that generate flux levels of 250-1000 suns. High flux levels add significantly to the expense of the optics and tracking mechanisms employed as well as the heat generated by the system.

For systems designed to concentrate sunlight in the 2-200 sun range, there is currently no alternative to single-crystal Si. One of the goals of this work is to explore such an alternative. Additionally, work is underway to develop a multi-junction, polycrystalline thin-film device technology. We have constructed an empirical model to predict the performance of these devices as a function of band gap pairs. The model uses NREL's data base to arrive at an expression for the reverse saturation current (J_0) as a function of band gap for previously measured polycrystalline thin-film devices. As opposed to more idealized models, this technique indicates what should be practically achievable performance levels for real-world devices. This model indicates that at one-sun, we may expect efficiencies as high as 26% for two-junction, series-connected devices. At 50 suns, this value approaches 31%. The implications of a 30% efficient, inexpensive concentrator cell technology is expected to provide motivation for further development of low-flux concentrator optics and modules.

2. Experimental

The high-efficiency CIGS devices fabricated at NREL employ a CdS buffer/window layer that is laid down by chemical bath deposition (CBD). The band gap of CdS is too low (2.4 eV) to assure transmission of all the useful light in the spectrum. Therefore, one attempts to limit the absorption in this layer by making the window thin. However, making the window layer too thin impacts the voltage of the device. It is postulated that this decrease in voltage is caused by shunt paths through the CdS. For these concentrator cells, we decided to trade off V_{oc} for an enhanced current, with the hope that these shunt paths would become saturated at higher flux levels.

Soda-lime silicate glass was used as the substrate. A 1-µ-thick molybdenum (Mo) layer was deposited by sputtering, and this serves as the back contact. The $CuInGaSe_2$ films were grown by NREL's three-stage co-evaporation process. First, an $(InGa)_2Se_3$ layer was deposited at 400°C, and this was followed by evaporation of Cu and Se at 550°C to make the film slightly Cu-rich. The composition was restored to a slightly Cu-poor one by the addition of $(InGa)_2Se_3$ again. To fabricate ZnO/CdS/CIGS structures, a 30-nm-thick CdS layer was first deposited by CBD. The bath composition was as follows: 0.0015 M $CdSO_4$, 1.5 M NH_4OH and 0.075 M thiourea. The temperature of the bath was increased from room temperature to 60°C in about 15 minutes, during which a thin CdS layer was deposited on the CIGS absorbers. A ZnO top electrode was deposited by r.f. sputtering in two layers. First, a 50-nm-thick ZnO film was deposited from a pure ZnO target, and this was followed by the deposition of a 200-nm-thick, Al-doped ZnO layer.

The CIGS concentrator cells were completed by the e-beam deposition of a Ni/Ag grid. The grid lines were 10 µm wide and 5 µm thick on a 150-µm pitch. The device area was 0.1 cm^2 using the standard concentrator cell area definition: total mesa area minus the area of the bus bars. The cells were isolated using lithography and a 20-second dip in 10% HCl. Finally, a 100-nm-thick layer of MgF_2 was applied as an anti-reflection coating.

3. Results and Discussion

Table 1 shows the performance parameters of the best CIGS concentrator cell as a function of concentration ratio.

Suns	Voc (mV)	Fill Factor (%)	Efficiency (%)
1.0	647	76.3	17.9
1.67	666	77.2	18.7
2.28	677	77.9	19.1
2.93	686	78.4	19.5
3.76	693	78.7	19.8
4.36	700	79.4	20.2
9.46	722	80.6	21.1
14.05	736	80.5	21.5

Table 1. Performance parameters for a CIGS concentrator cell under the direct spectrum.

The high fill factor at 14 suns (80.5%) implies that this device is not yet series-resistance limited. Figure 1

represents the I-V characteristics of the best CIGS concentrator cell at peak efficiency.

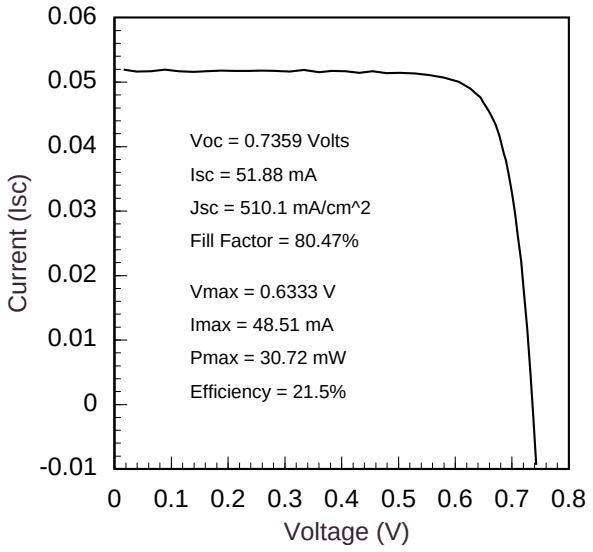

Figure 1. I-V characteristics of a CIGS concentrator cell at peak efficiency (14.1 suns).

This is the first verified report of a polycrystalline thin-film solar cell with an efficiency above 20%. We measured these devices under a flash simulator for a variety of flux levels up to 50 suns concentration and their efficiency was still above 20%. Figure 2 is a plot of the efficiency as a function of concentration ratio for these measurements.

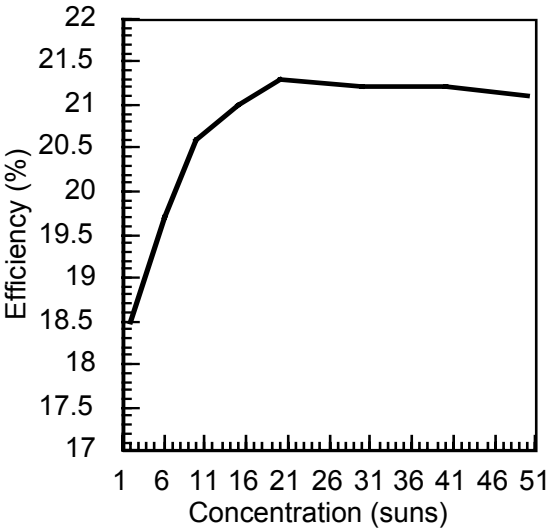

Figure 2. Efficiency as a function of concentration ratio for a CIGS concentrator cell.

These CIGS concentrator cells were fabricated from device structures that were deposited on glass substrates. Glass is problematic from a thermal transport perspective. For this technology to succeed we will need to replicate these results on a conductive substrate such as stainless steel. We have begun working on CIGS structures deposited on stainless steel with encouraging results. Although there is a performance differential between the best devices on soda lime glass substrates and the best results obtained on stainless steel, that differential is expected to narrow as a function of operation under concentration. There has been considerable speculation about the possibility that certain traps and other recombination mechanisms may be saturated during operation under concentrated light, thereby leading to enhanced performance. We intend to pursue studies related to these issues in the near term. However, we do know that parasitic shunts are certainly ameliorated by operation under concentration. Since one of the problems encountered when using stainless steel seems to be shunting, we expect that these devices will perform well under concentration.

Similarly we are engaged in experiments that are designed to investigate the affect of concentrated illumination on devices that use alternative buffer/window layers. We will be looking at Cd-free devices among other alternatives.

Conclusions: Although the marriage of thin-film PV devices and concentrating optics may strike many as being counter-intuitive, there are several reason to pursue this approach. The cost of a concentrator system is dominated by the optics, tracking mechanism, and other balance-of-systems considerations. However, a recent analysis of manufacturing issues for concentrating PV systems indicates that between 33% and 35% of their cost is related to the PV cells. Reducing the cost of the cells by an order of magnitude would thereby imply a 30% reduction in total system cost. Additionally, the development of a multi-junction polycrystalline thin-film device technology offers the promise of significantly enhanced performance as well as reduced cost. Finally one might also consider issues of material availability and scale up.

Acknowledgments: This work was performed under funding from the U. S. Department of Energy's High Performance PV Initiative. The authors wish to thank Dan Friedman of NREL's High Efficiency III-V team and Keith Emery of NREL's Characterization team for their assistance and insights.

References:

1. M. A. Contreras, B. Egass, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon, and R. Noufi, Progress in Photovoltaics: Research and Applications. 7, 311 (1999).

2. T. Nigami, Y. Hashimito and, S. Nishiwaki, Solar Energy Materials and Solar Cells: 67, 331 (2001).

3. W. Fuchs, and R. Klenk, *Proc. 2nd World Conference on Photovoltaic Solar Energy Conversion,* edited by J. Schmid, H. A. Ossenbrink, P. Helm, H. Ehmann and E. D. Dunlop, Office of Official Publications of the European Communities, p. 381 (1998).

4. H. L. Cotal, D. R. Lillington, J. H. Ermer, R. R. King, N. M. Karam, S. R. Kurtz, D. J. Friedman, J. M. Olson, J. S. Ward, A. Duda, K. A. Emery, and T. Moriarty, *Proc. of the 2000 IEEE Photovoltaic Specialists Conference*, Alaska, p.955 (2000).